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About Me Jeff Morgenthaler

- 1988–1995 soft X-ray instrumentation
 - MIT CCD lab senior thesis: Soft X-ray Quantum Efficiency of prototype ASCA CCD detectors (Morgenthaler 1990)
 - X-ray Quantum Calorimeter (XQC) sounding rocket payload development (McCammon *et al.* 2002)
- 1995–Present soft diffuse X-ray background, ISM data analysis
 - Shuttle STS-54 payload: Diffuse X-ray Spectrometer (DXS) (Morgenthaler 1998; Sanders *et al.* 2001)
- 1997–2002 Comet Hale-Bopp data analysis of optical emission lines ([O I] 6300 Å, H α , OH 3080 Å, [C I] 9850 Å: Morgenthaler *et al.* 2001, 2002; Harris *et al.* 2002; Oliverson *et al.* 2002)
- 1997–Present Io plasma torus observations (Oliverson *et al.* 2001)
- 2002–Present Io plasma torus data analysis

Oxygen Emission in Io's Atmosphere as a Probe of the Plasma Torus

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Outline

- Basics
 - What: Io plasma torus. Io is the most volcanic body in the solar system. Kicks off stuff that is swept up in Jupiter's magnetic field.
 - Where: around Jupiter roughly at Io's orbital radius
 - When: we limit observations to a ~ 4 month period every 13 months (we get 2–8 weeks of observing time a year)
 - Why: Unique (in solar system) source of plasma within a magnetosphere, fundamental understanding of plasma physics, plasma interaction with moons, moon atmospheres, "its there"
 - How: McMath-Pierce solar telescope stellar spectrograph, lots of computer time (MEF)
- What have we learned?
 - Io [O I] emission tracks model of plasma torus density (Oliverson *et al.* 2001)
 - Io [O I] emission tracks other torus activity diagnostics (Oliverson *et al.*, in preparation)
 - Automatic reduction of 13 years worth of ground-based data is hard but not impossible.

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Io: the moldy pizza



Fig. 1.— Mercury compared to 7 large moons of the Solar System (Kaufmann & Freedman 1999).

- One of the big 7 moons in the solar system
- About the same size as Earth's moon
- The most volcanic body in the solar system

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Volcanism on Io

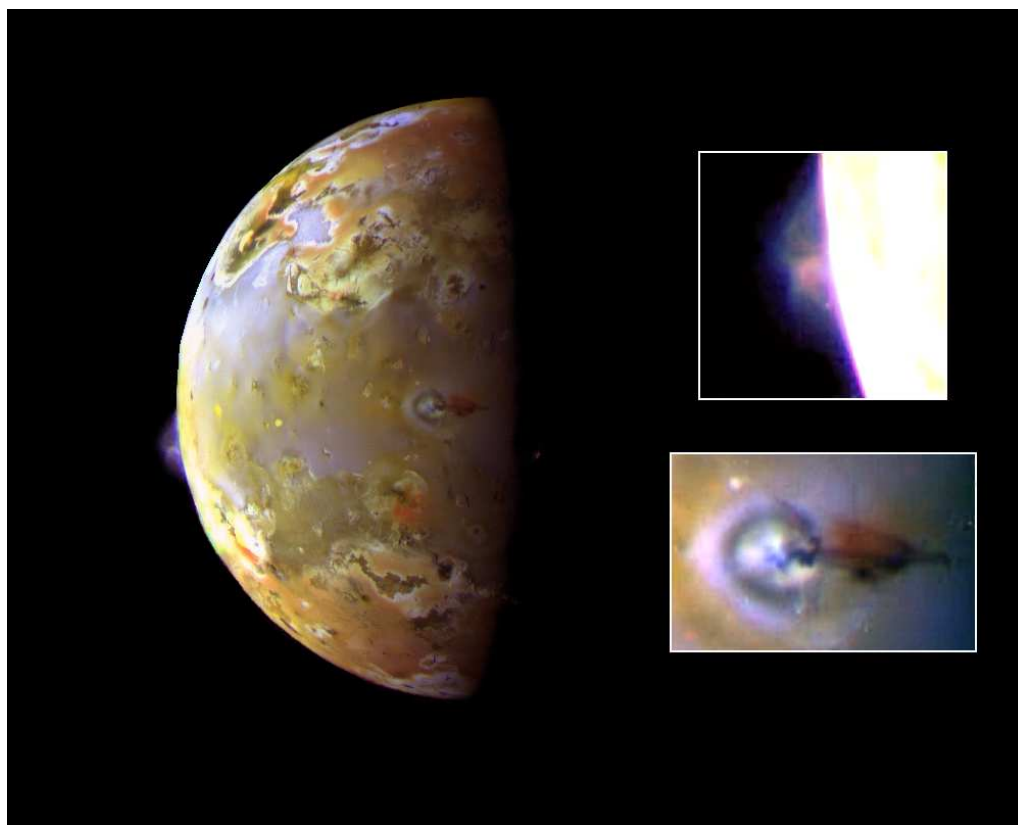


Fig. 2.— Evidence for volcanism on Io (<http://galileo.jpl.nasa.gov/images/io/ioimages.html>).

- Caused by tidal forces between Io and Jupiter which are maintained by orbital resonances with Europa and Ganymede ($2\times$ and $4\times$ period of Io)
- Material released = SO_2 , SO
- Directly or indirectly the primary source of Io's atmosphere
- Other atmospheric constituents: S_2 , S, O, Na, K, Cl, [NaCl], H

Io Immersed in the Jovian Magnetosphere

- Jupiter's magnetic field
 - tilted by 10° with respect to rotation axis
 - offset from center of rotation by $0.13 R_J$
 - not a simple dipole
 - rotates every 9.925 hours
- Ions bound longitudinally to field lines but free to move in latitude
- Centrifugal and magnetic forces balance so torus tilt is 7°
- Flow of material down magnetotail induces east-west electric field
- Various torus structures:
 - cold inner torus: inward diffusion
 - ribbon near Io's orbit: highest density
 - warm outer torus: $T_e = 5 \text{ eV}$ with long, hot tail
- Io orbits every 42.5 hours; ion whips around and hits the other side of Io at 57 km s^{-1}
- Plasma interaction with Io (and other moons) is primary atmospheric loss mechanism
- **In the frame of reference of the torus, Io moves $\pm 0.75 R_J$ vertically and $\pm 0.75 R_J$ radially through these structures**

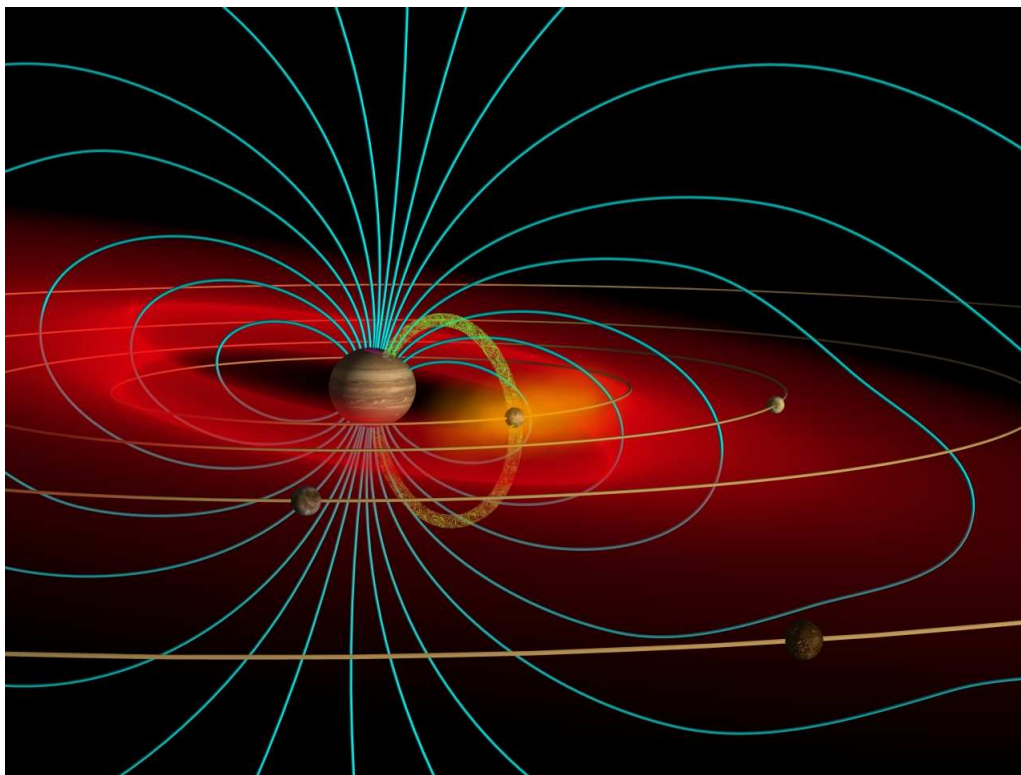


Fig. 3.— Visualization of Jovian magnetic field showing Io flux tube, Na cloud, S II torus (<http://www.lowell.edu/users/spencer/digipics.html>).

Narrow-band Images of the Torus

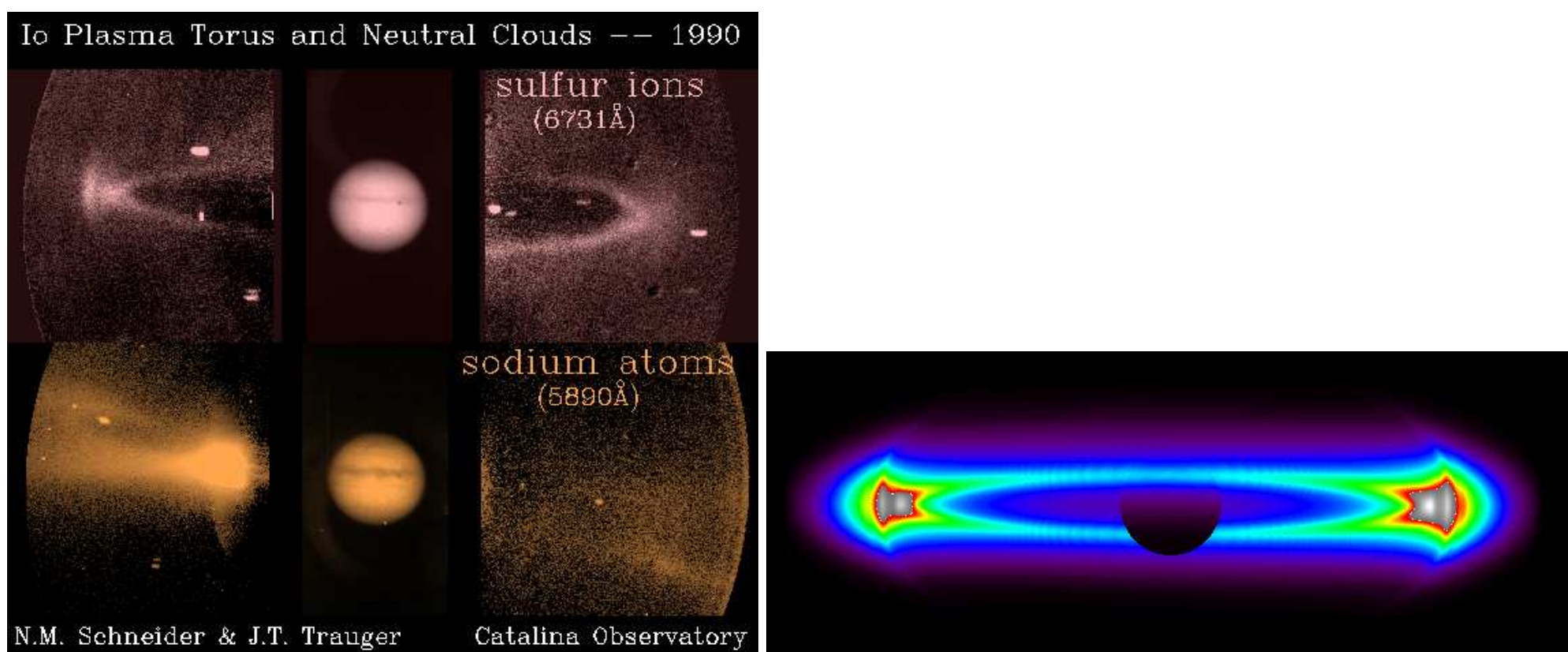


Fig. 4.— Narrow-band images of S II 6731 Å (top left) and Na 5890 Å (bottom left) in the Jovian system (Courtesy N. M. Schneider & J. T. Trauger). Right: Portable Io Torus Toolbox (PITT) model of S II 6731 Å (Courtesy R. C. Woodward).

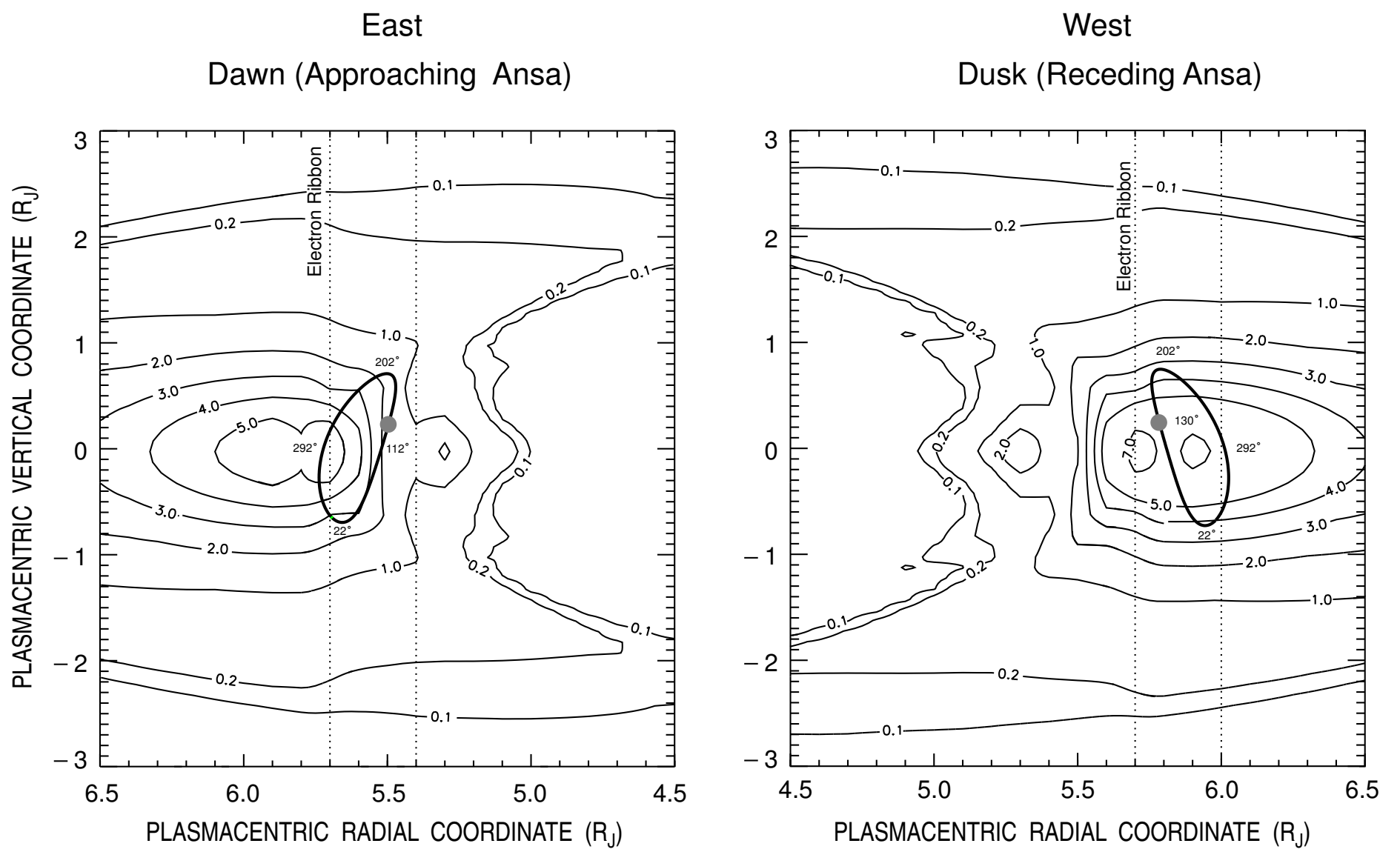


Fig. 5.— Io’s position in the rest frame of the plasma torus at eastern and western elongation (Oliversen *et al.* 2001, fig. 7). Coutours indicate electron density based on Voyager data (Bagenal 1994).

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Io/plasma interactions

All kinds of interesting dynamics having to do with a conducting obstacle in a plasma flow

- Pile-up (no bow shock)
- Induced current from collisions in ionosphere (10^6 A)
- Atmospheric ablation
- Mass loading
- Wake
- Charge exchange resulting in weird jets
(http://ganesh.colorado.edu/~ray/animtorus/torus.cgi?sample_text=75)
- Flux tube
- Other things
- **Electron collisional excitation of atmospheric species, e.g. Oxygen**



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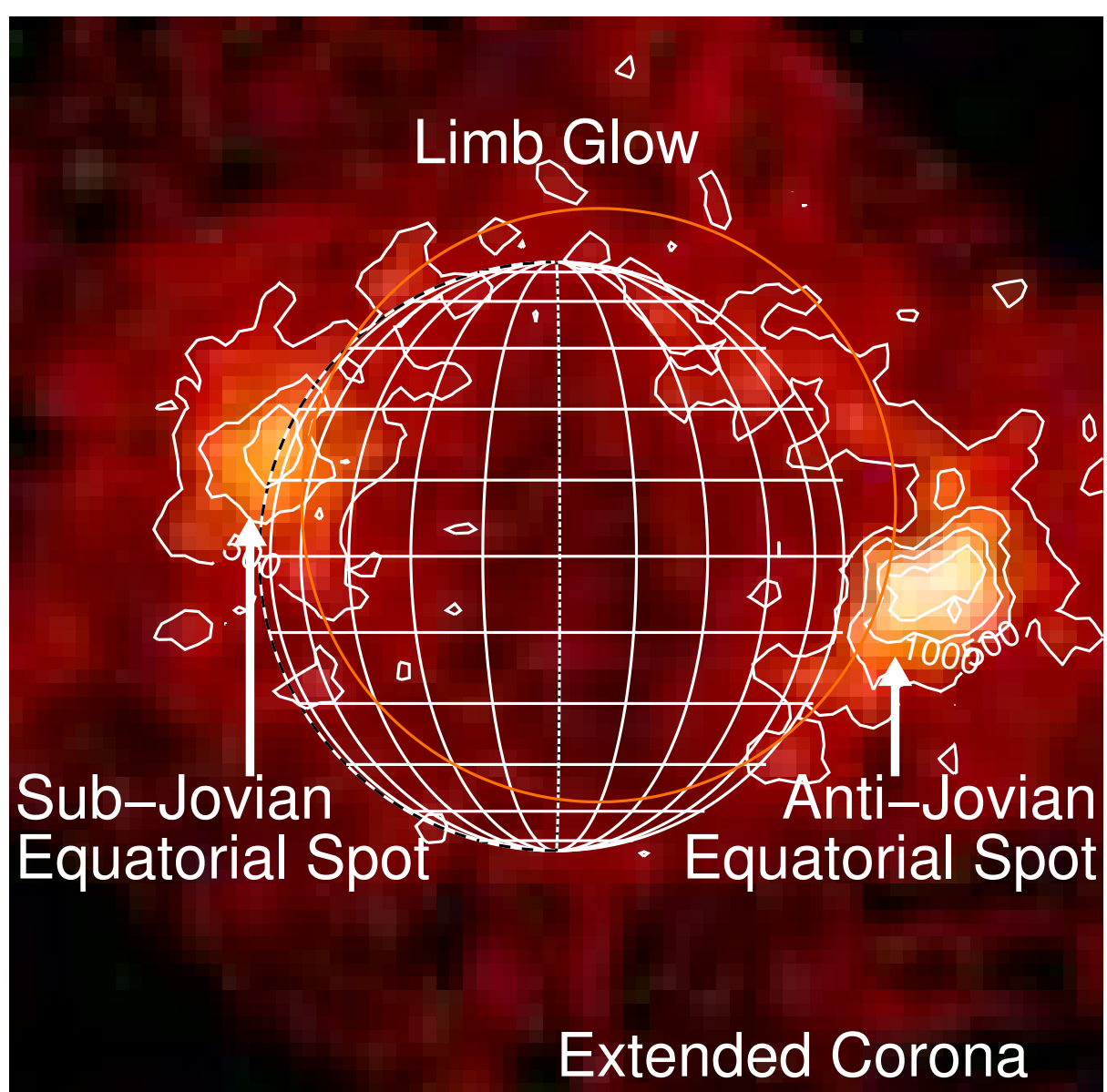


Fig. 6.— STIS O I] 1356 Å image of Io at eastern elongation (Retherford *et al.* 2000; Retherford 2002). Orange circle is O I] 1359 Å emission

Ground-based observations of [O I] 6300 Å

- Detected in 1990 (Scherb & Smyth 1993)
- McMath-Pierce solar telescope, stellar spectrograph
- 1.5 m telescope, $f = 76.2$ m
- Unocculted beam (no diffraction spikes)
- Works best in the ecliptic
- Beam focused onto a Bowen-Walraven image slicer with a $5''.2 \times 5''.2$ FOV
- Echelle spectrograph
 - $\tan \theta = 2$
 - lines = 20,100 per inch
 - $R = 120,000$ at 6300 Å (50 milliÅ, 2.5 km s^{-1})
 - TI CCD similar to HST WFPC I (i.e. old, slow readout)
 - Temperamental, hard to repeat alignment procedures (working on that)
 - Available at night nearly continuously (share with one other user)
 - No adult supervision

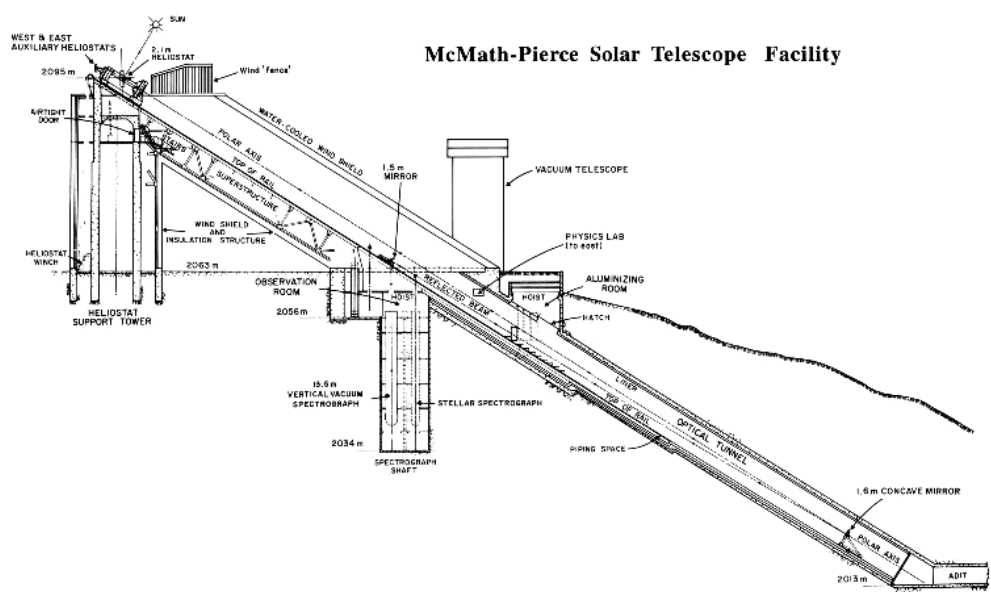


Fig. 7.— McMath-Pierce Solar telescope. Figures courtesy of NOAO/AURA/NSF.

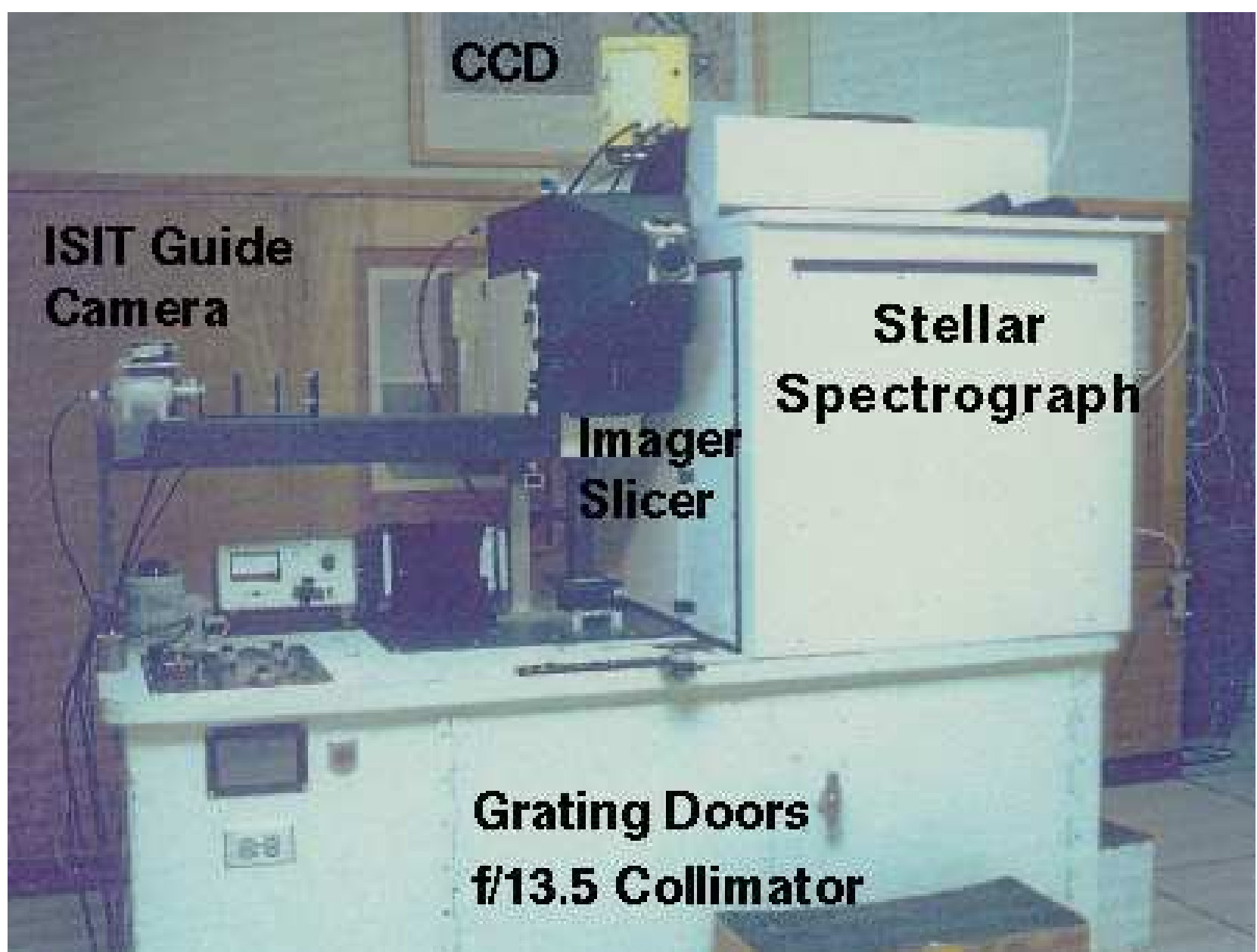


Fig. 8.— McMath-Pierce solar telescope facility Stellar Spectrograph (SSG).

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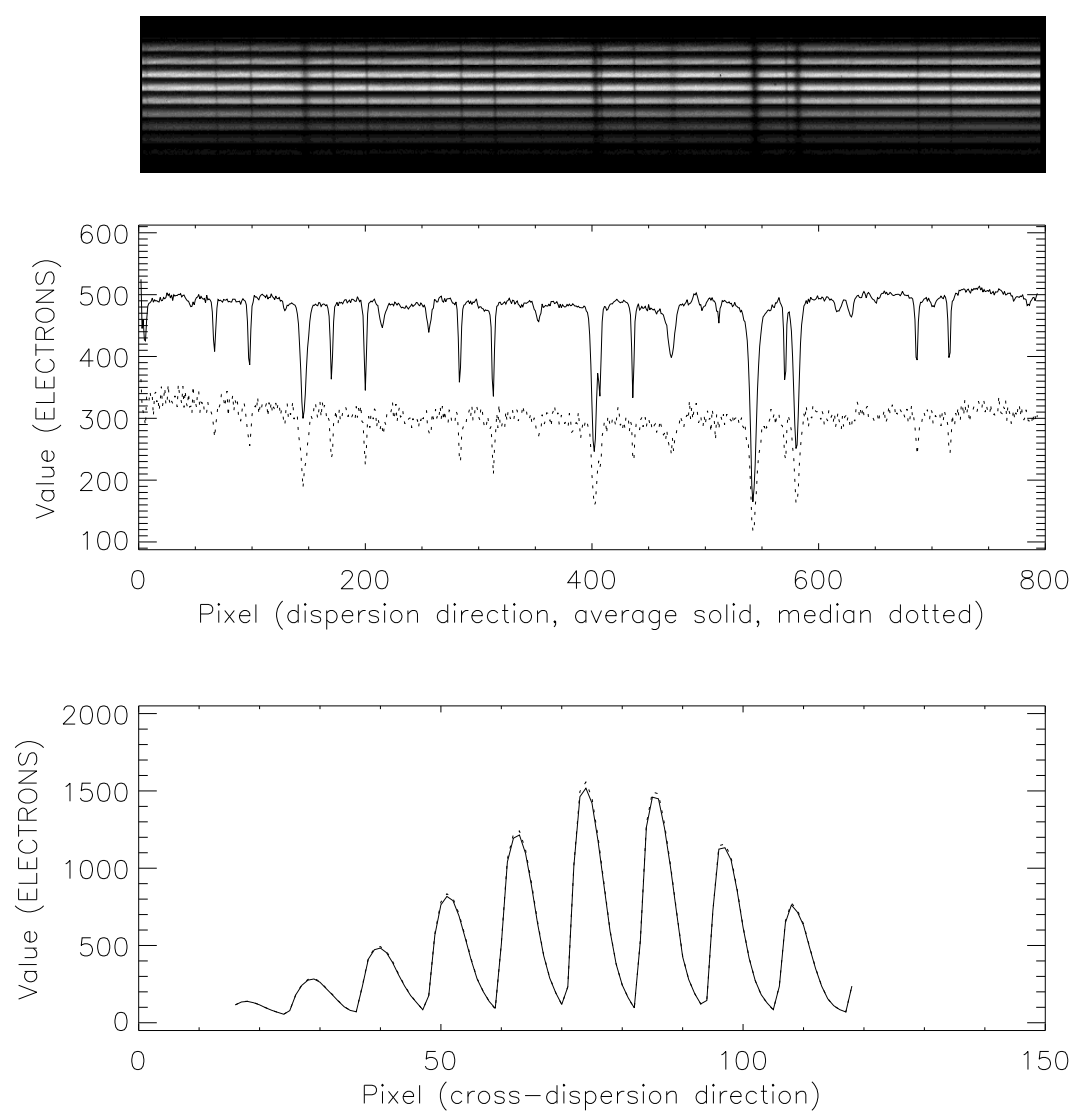


Fig. 9.— Processed Io [O I] 6300 Å spectral image recorded 2002 Jan 26 by the stellar spectrograph at the McMath-Pierce solar telescope facility (upper). Spectral extractions are shown below in the dispersion (middle) and cross dispersion (lower) directions. Seeing this night was $\sim 3''$.

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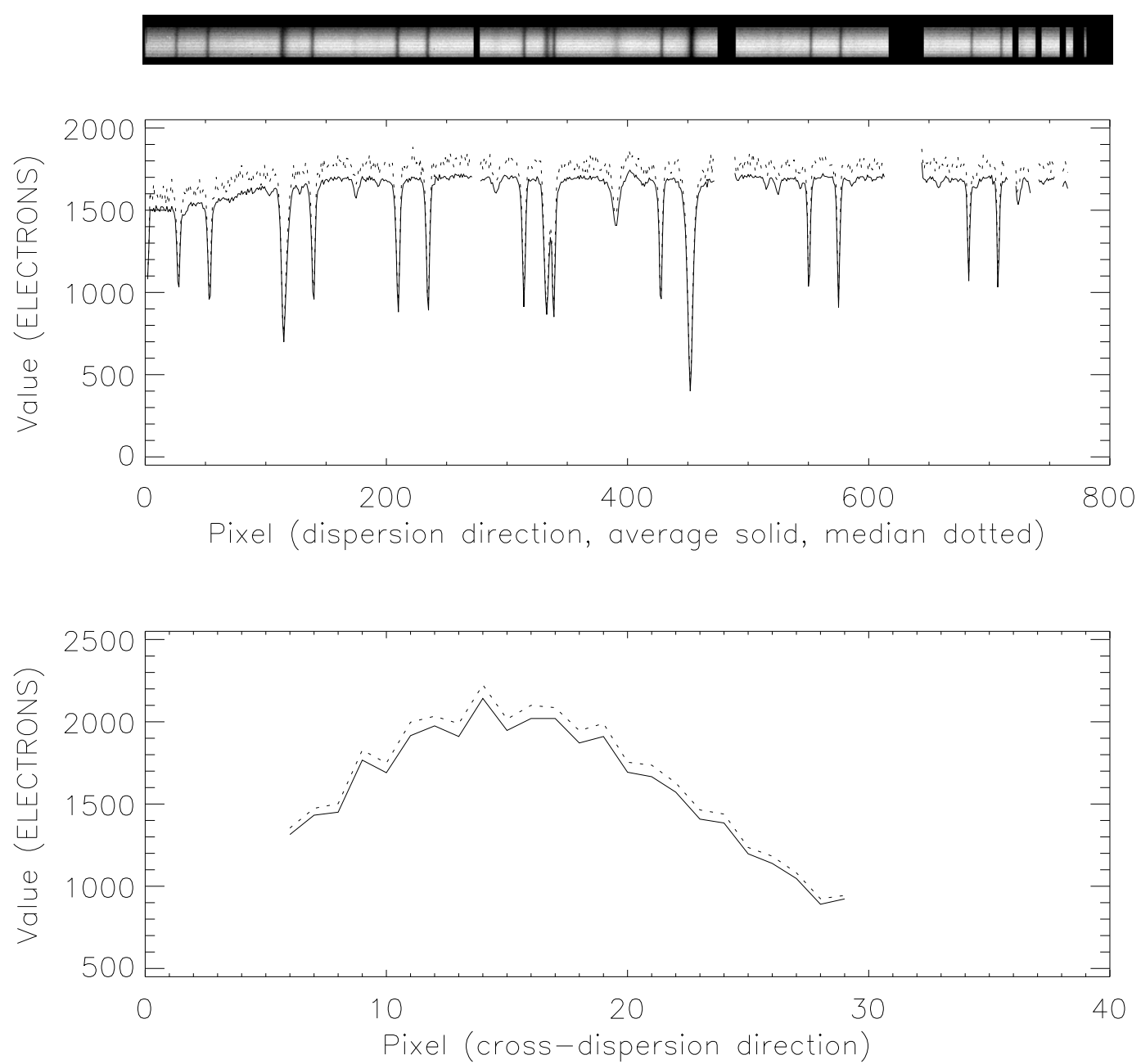


Fig. 10.— Unusual spectrum recorded 1997 Oct 14. CCD is binned in the Y direction – that is not what is unusual about this spectrum.

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Lather, Rinse, Repeat

- Over 3000 spectra recorded since 1990
- Over 13,000 calibration (bias, flat, comp, etc.) images
- Oliverson *et al.* (2001) report on hand reduction of 1000 spectra
- Not interested in spending my NRC fellowship hand reducing 2000 spectra
- Developed automated data reduction and spectral fitting software using basic artificial intelligence techniques
 - Robust algorithms process the data one time through
 - Results stored in an IDL astro-util ZDBASE
 - Analysis programs find patterns (e.g. fit polynomials to parameters that vary slowly with time)
 - Data are corrected or re-reduced using global trends
- Automatically extracted all spectra in 6 days of computer time (completed 2003 June 26)
- Currently working on automated fitting software

Automated Fitting Software

- Parameterized Function Object (PFO)
 - Object oriented non-linear least-squares curve fitting routine
 - Allows fitting function to be easily modified at runtime
 - Written in IDL (Image Display Language)
 - Based on astro-util package MPFIT
- Solar System Objects (SSO)
 - Interface solar (Moore *et al.* 1966; Pierce & Brekenridge 1973; Allende Prieto & Garcia Lopez 1998) and atmospheric (e.g. HITRAN; Rothman *et al.* 2003) line lists to PFO software
 - Handles multi-reflection, multiple Doppler shifts
 - Soon: Interface JPL HORIZONS ephemerides to IDL data structures
- Software works together to allow a physically realistic model of the entire target/atmosphere/instrument system
 - Free parameters are: dispersion relation, solar and Io Doppler shifts, continuum flux, line equivalent widths and line widths (Voigt profiles are used for strong lines)

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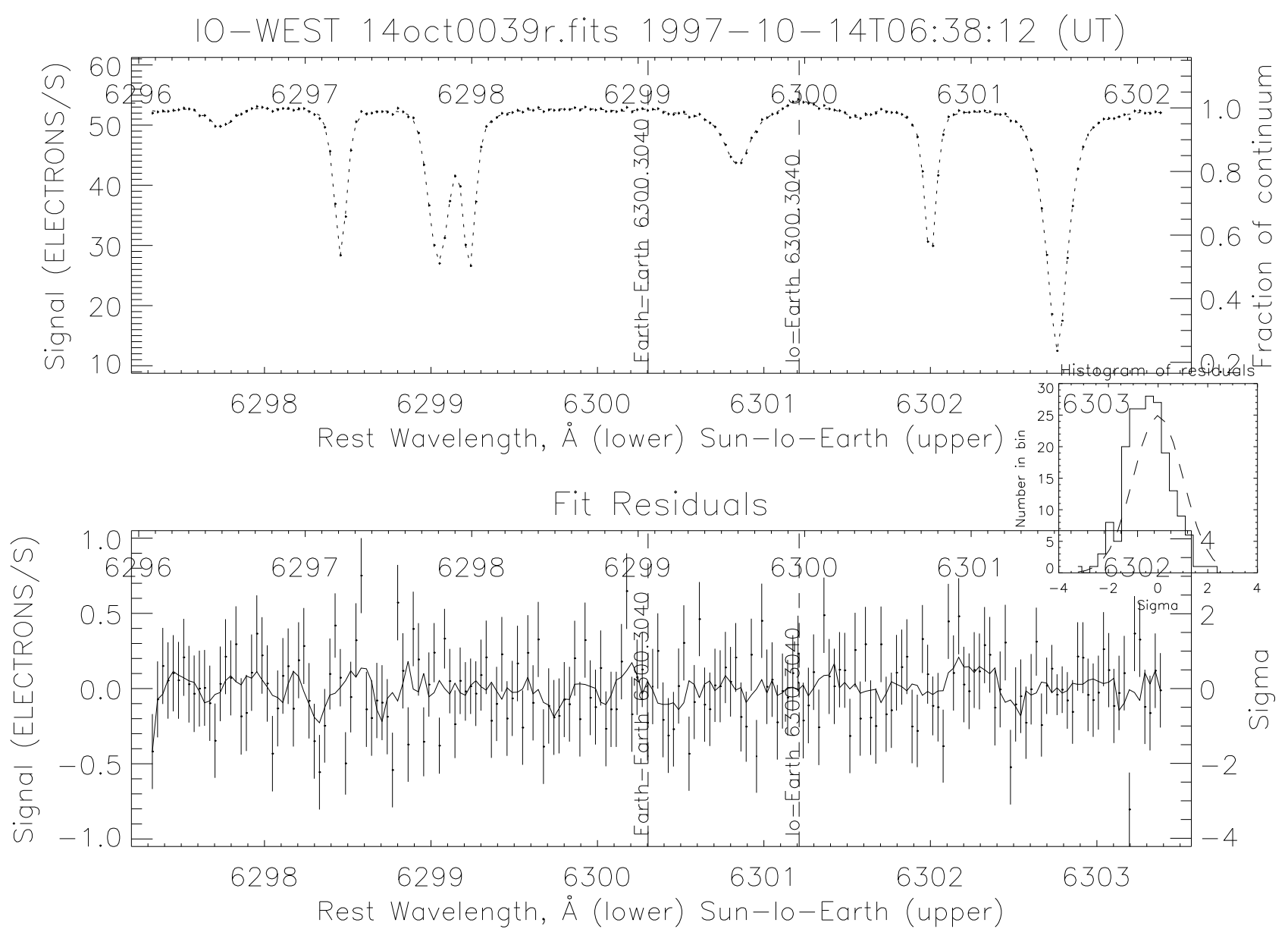


Fig. 11.— SSO fit to “unusual spectrum” recorded 1997 Oct 14. 23 lines were used in the fit.

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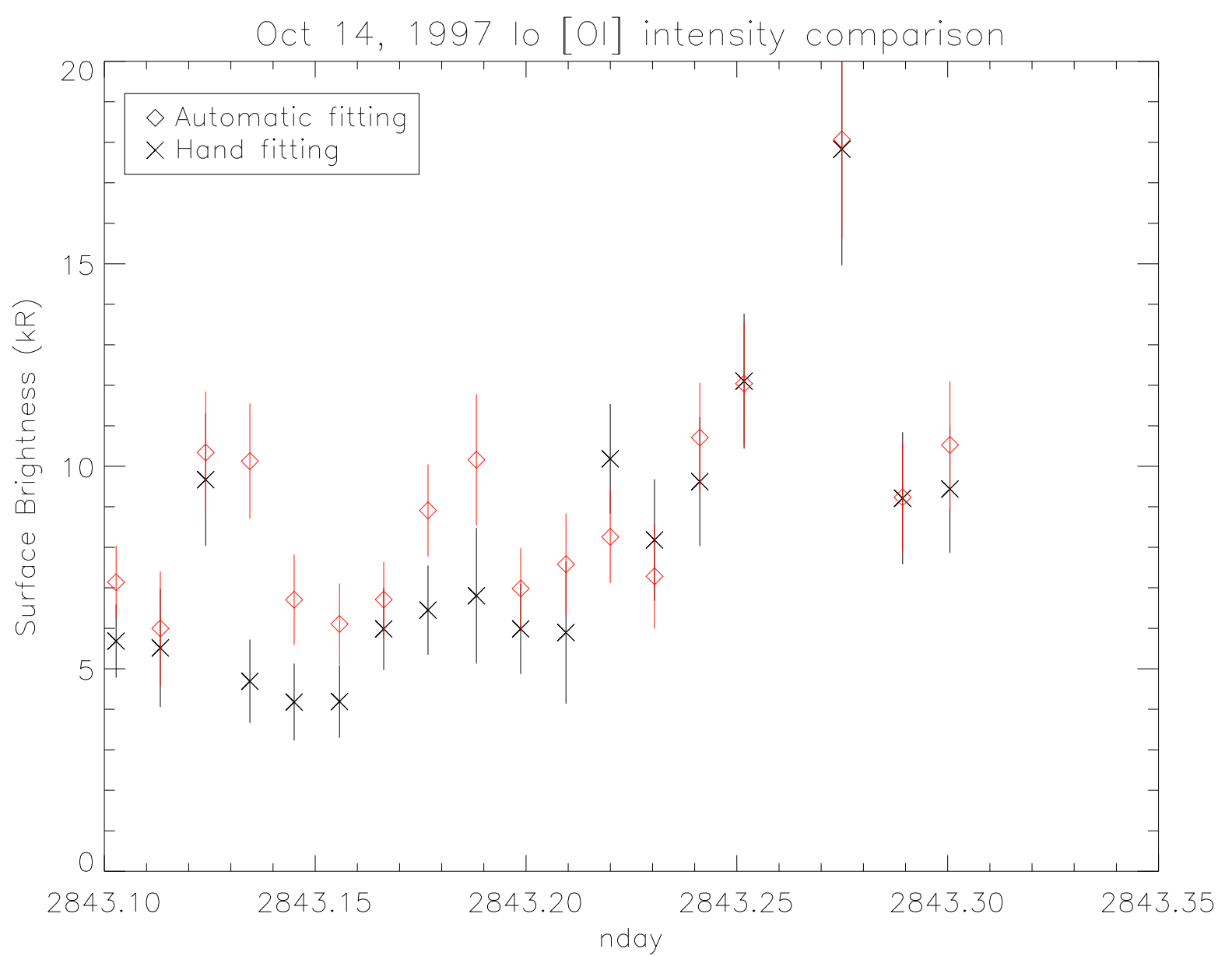


Fig. 12.— Comparison between Io [O I] intensities fit by hand and fit automatically.

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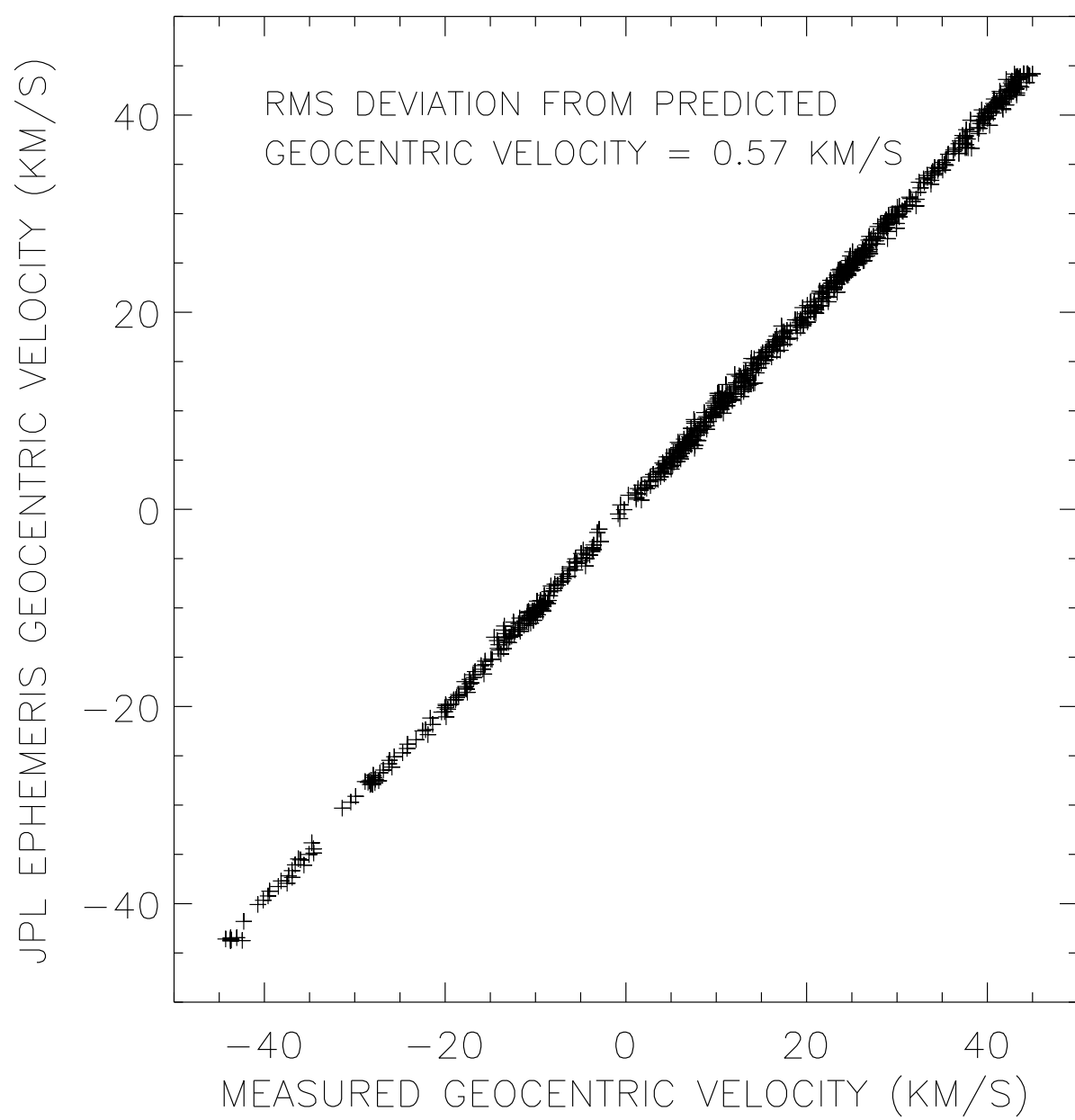


Fig. 13.— Io [O I] fit Doppler velocity vs. Io geocentric ephemeris velocity (Oliversen *et al.* 2001, fig. 2).

Figure 2

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Link between plasma and $O(^1D)$ emission

- Plasma torus tilted 7° relative to Io's orbit
- Torus rotates faster than Io orbits (57 km s^{-1} at Io)
- Even if torus was a simple doughnut, plasma conditions at Io should correlate with Io's magnetic longitude (system III)
- Oliverson *et al.* (2001) show this correlation based on 1000 measurements recorded over 10 years
- Detailed (but static) model of the plasma torus can track the data well in some cases (Oliverson *et al.* 2001, figs. 10–11)
- **[O I] emission seems to be an effective *in situ* proxy for torus plasma density**

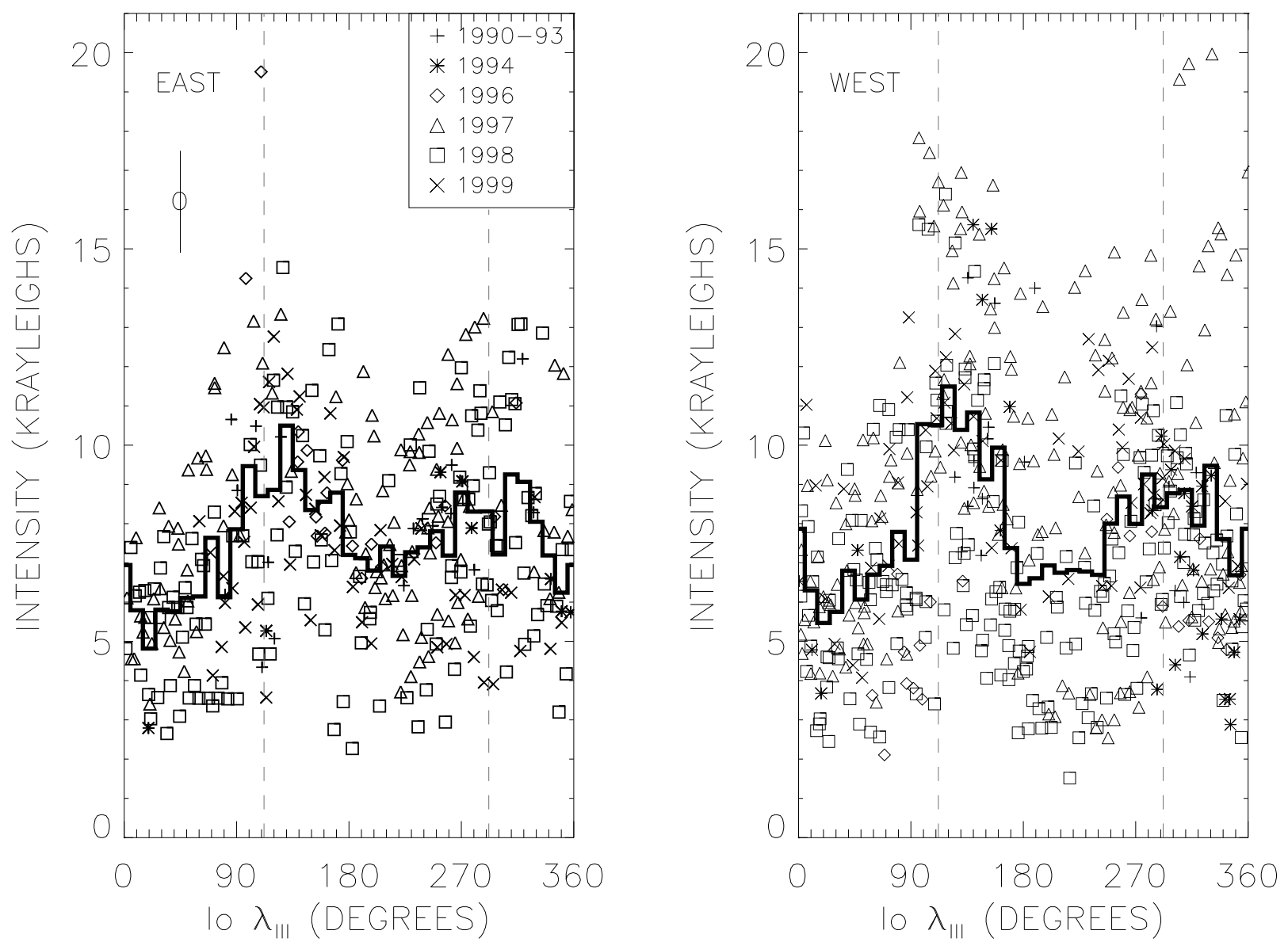


Fig. 14.— Measured Io [O I] intensities over a 10-year period as a function of Jovian magnetic longitude (system III) (Oliversen *et al.* 2001, fig. 4). Solid line is average over 10° bins.

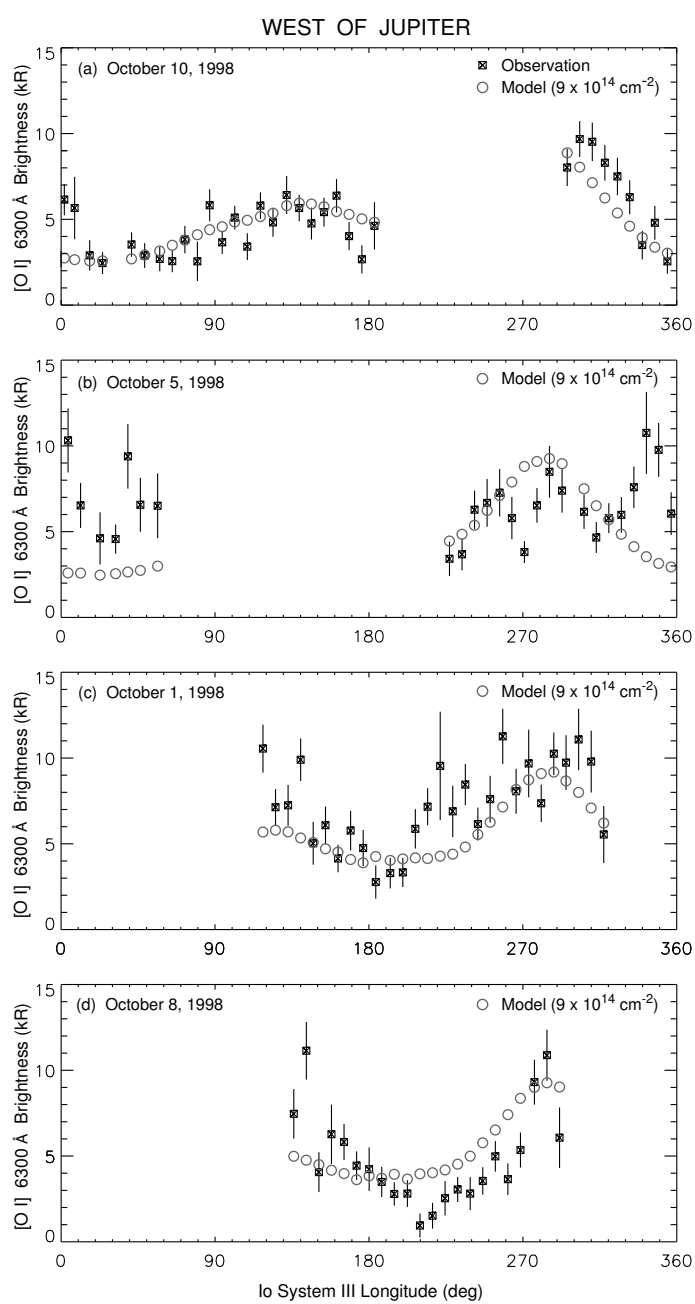


Figure 10

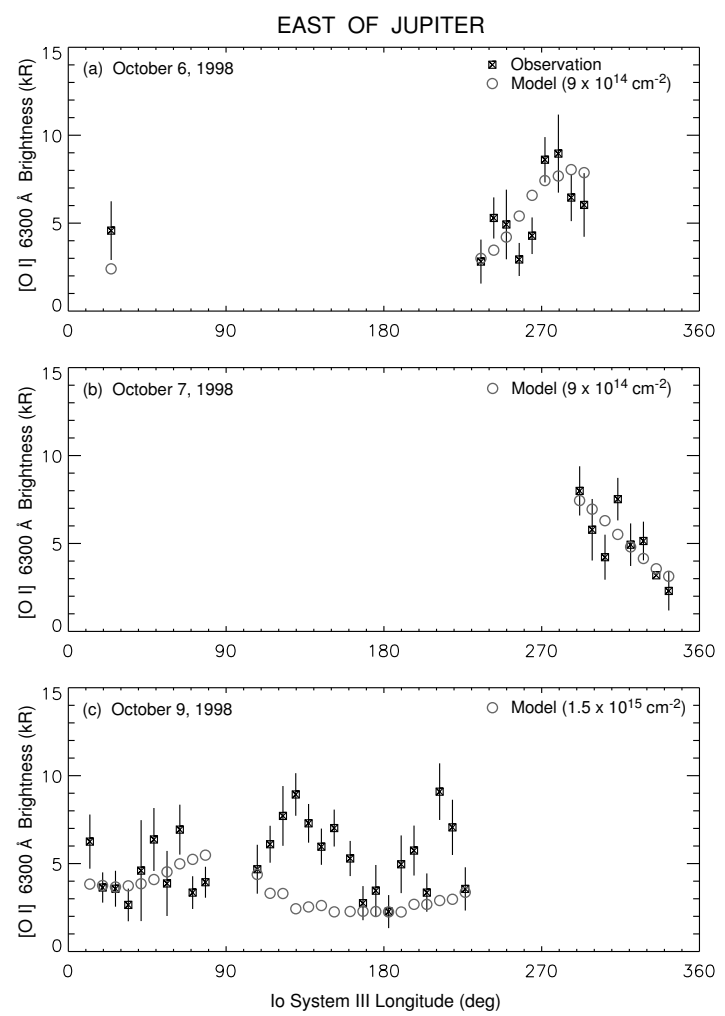


Figure 11

Fig. 15.— Measured and modeled [O I] 6300 Å emission from Io (Oliversen *et al.* 2001, figs. 10–11).

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Correlating Multiple Datasets

- Our “unusual day,” 1997 Oct 14 happens to be during an HST/STIS observation (Roesler *et al.* 1999)
- STIS sees neutral and ion emissions increase
- Simultaneous [S II] 6731 Å images of the torus are generally included in the [O I] observing campaigns (e.g. Woodward *et al.* 2000)
- Persistent, or at least repeating azimuthal asymmetry is seen in the [S II] 6731 Å torus at this system III longitude during this time period

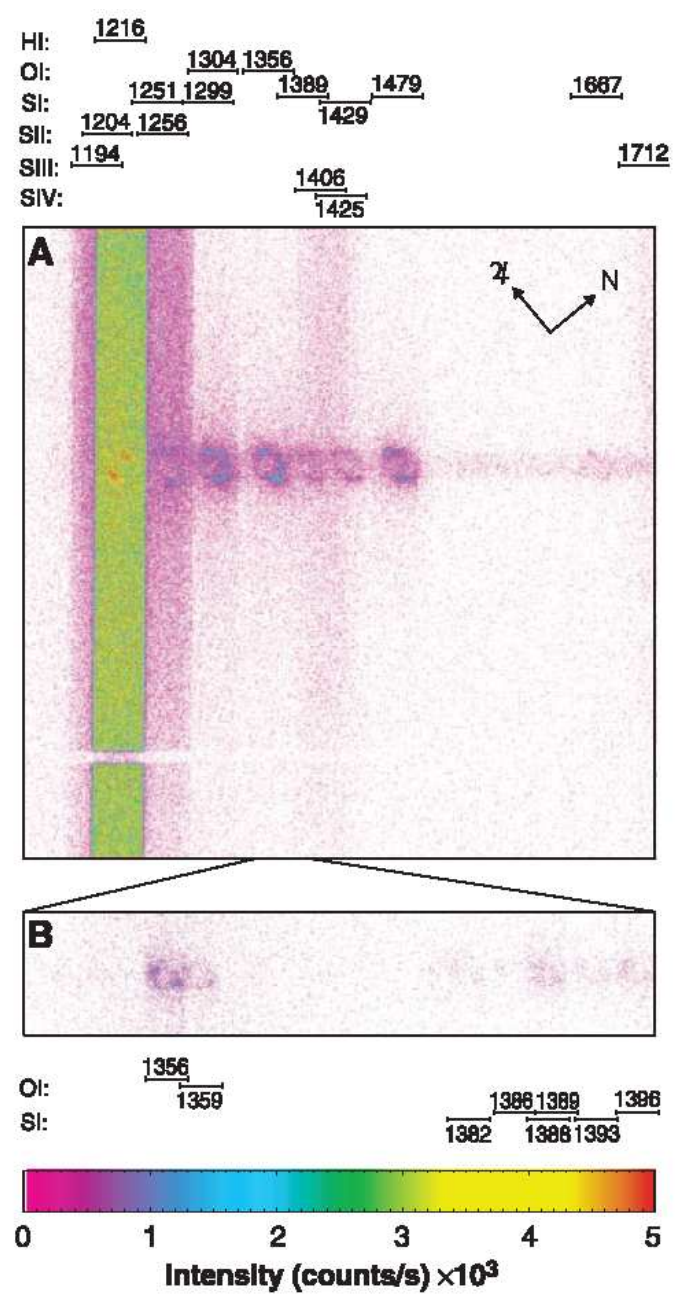


Fig. 16.— Sum of raw STIS data 1997 Oct 14 (Roesler *et al.* 1999, fig. 1). Extended emission from the torus is seen in the ion lines.

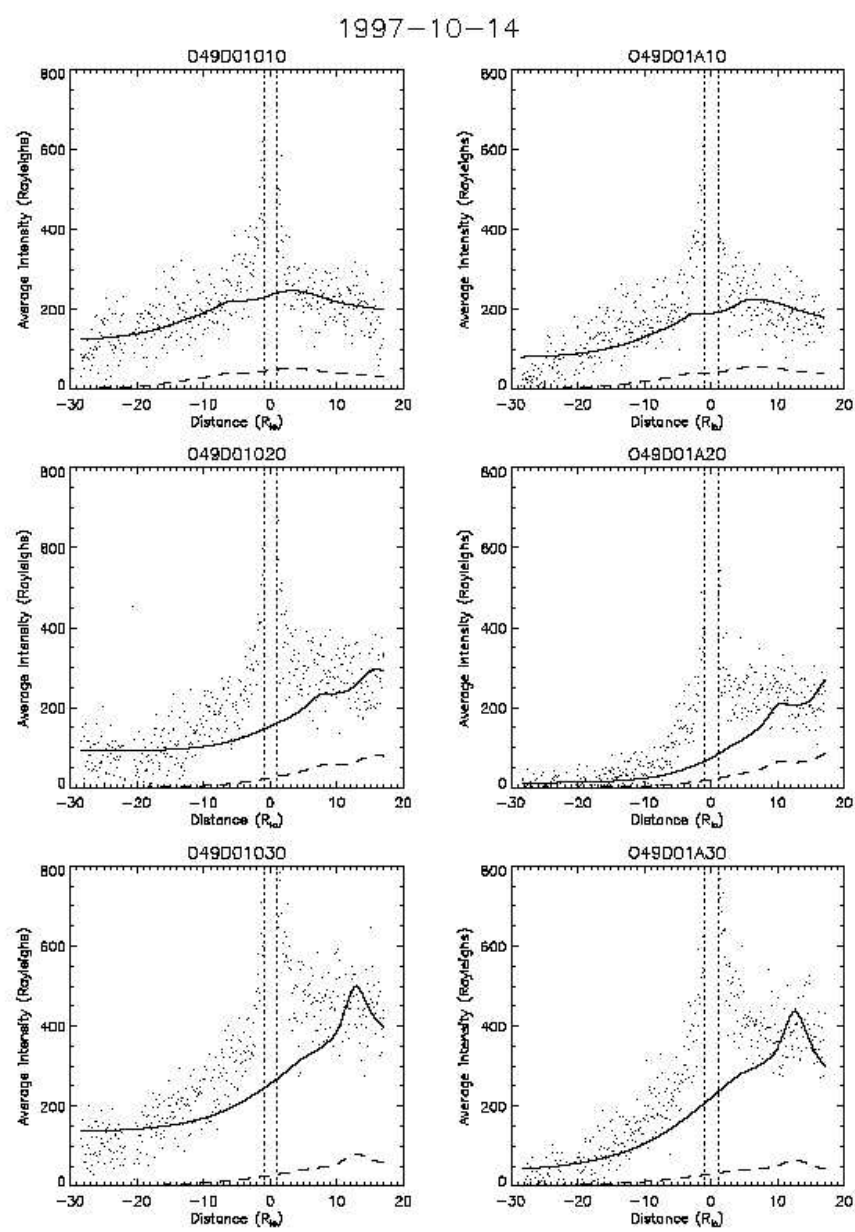


Fig. 17.— S II 1256 Å profiles on 1997 Oct 14 for each of the STIS G140L images. The edges of the disk of Io are shown as dotted lines. PITT model of torus emission is shown (dashed lines) and scaled and offset to match data (solid lines).

1998-08-23

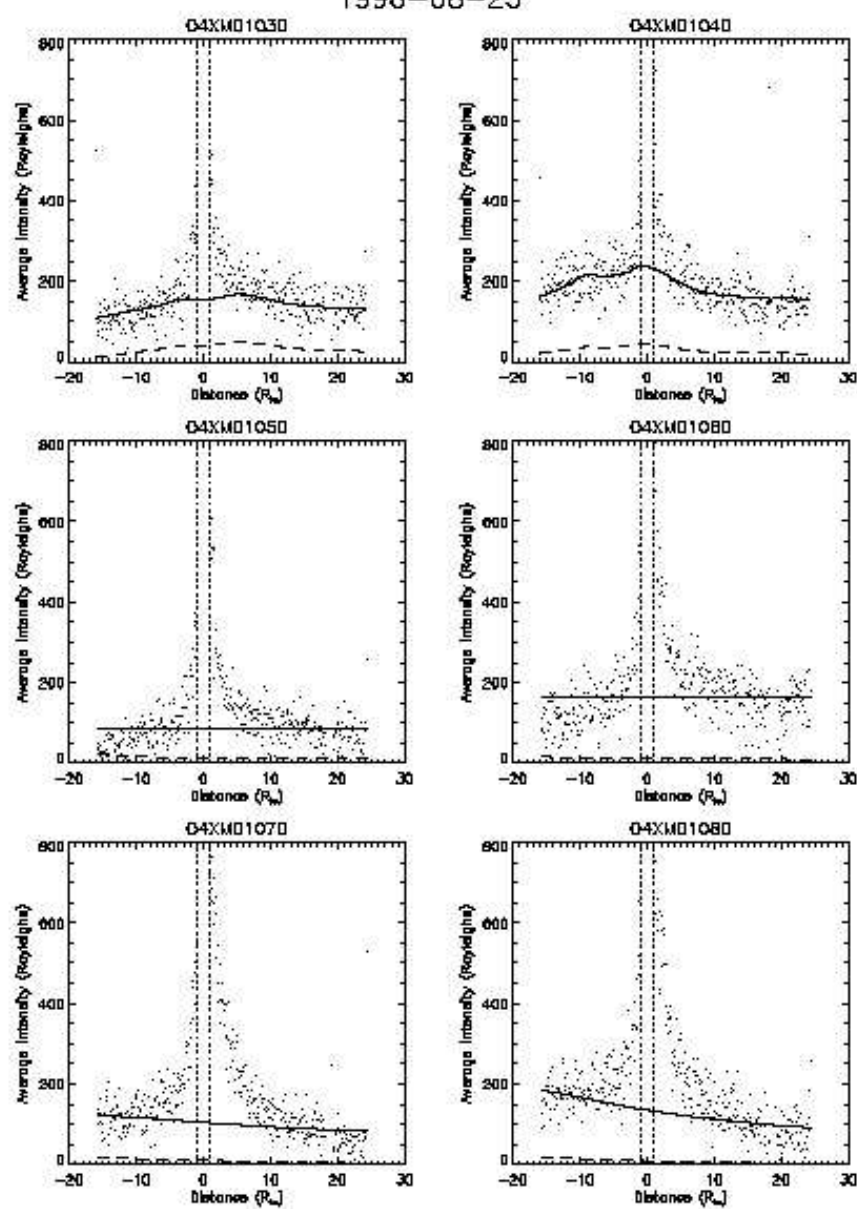


Fig. 18.— S II 1256 Å profiles on 1998 Aug 23. Compare to fig. 17.

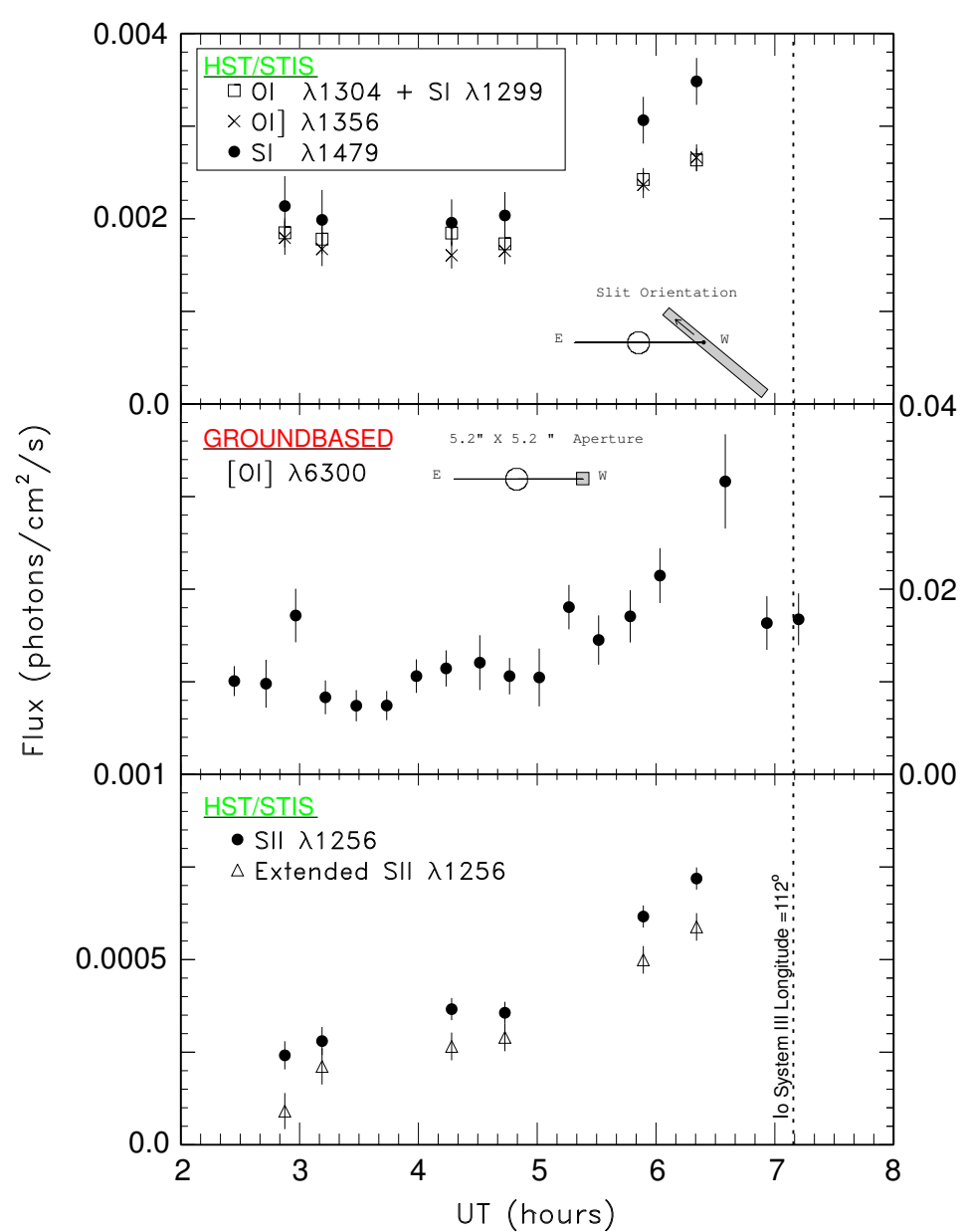


Fig. 19.— Comparison of Io atmospheric emissions for neutral (top) and ion (bottom) ultraviolet emission lines from HST/STIS and the [O I] 6300 Å emission line (middle). The UV ion results depend on the subtraction of the background torus. Peak in flux occurs before peak calculated by model.

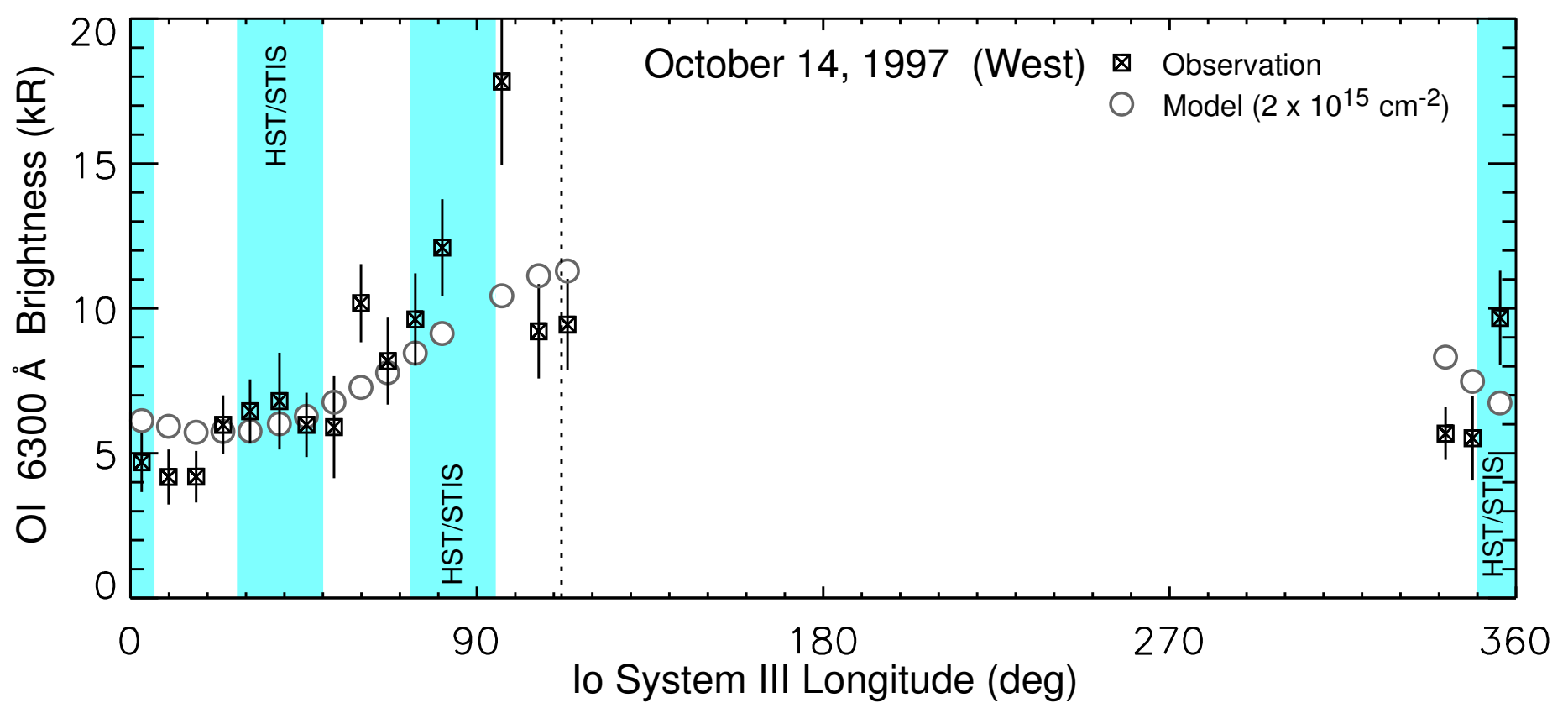


Fig. 20.— Model Io [O I] surface brightness vs. observations for 1997 October 14. Simultaneous HST/STIS ultraviolet measurements for O and S emissions from Io were obtained in the shaded areas.

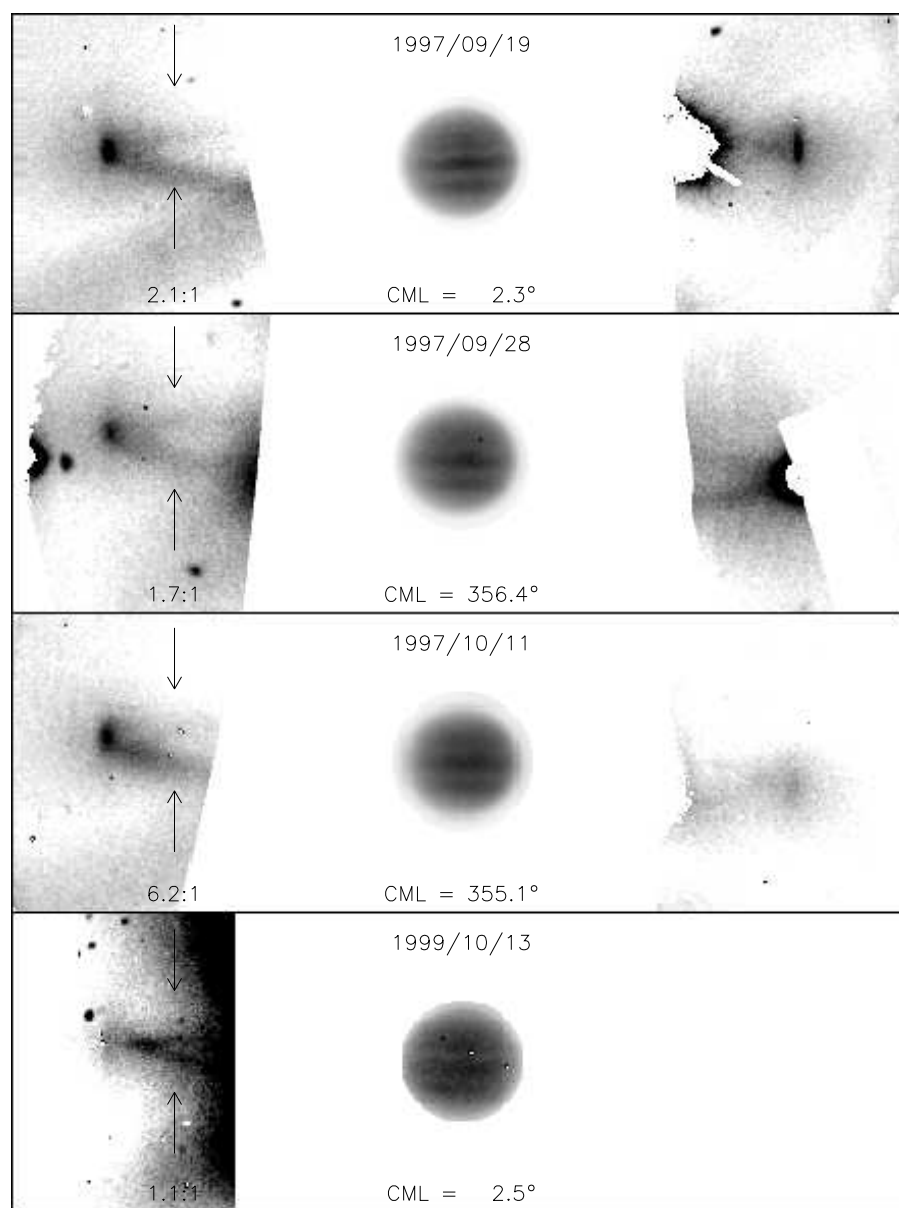


Fig. 21.— Narrowband images of the Io torus in [S II] 6731 Å. Jupiter is attenuated by a neutral density filter. The Galilean moons, such as Io, interfere with the observations. A persistent, or at least repeating azimuthal asymmetry in the [S II] 6731 Å torus is seen in the 1997 Sept–Oct timeframe (Woodward *et al.* 2000). [S II] images from 1999 (last panel) and other authors (e.g. fig. 4) do not always show asymmetries.

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Do we have a believable “smoking gun?”

- Maybe
- Azimuthal enhancement in the plasma torus that seems to persist over at least a several week time period around 1997 Oct 14
- Enhancement in plasma torus seen in STIS data
- Io brightens in neutral UV and optical lines on 1997 Oct 14
- Io brightens in UV ion lines (model dependent)

What does it mean?

- Ground-based [O I] 6300 Å observations can be used as a proxy for torus activity
- We can begin to understand the dynamics of the torus system

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Future plans

- Full reduction of ground-based [O I] data needed, complete with upper limits on days with weak signal
- Close to closing the loop on fully automated spectral extraction and fitting process
- Accurate ephemeris data for each Galilean moon during each of the 3000+ observations is needed
- Unbiased statistical treatment essential for believability of [O I] 6300 Å dataset
- [O I] 6300 Å dataset will be optimally reduced and archived, hopefully in the PDS
- Web interface to ZDBASE of (Oliversen *et al.* 2001) results is operational
- Continued reduction of [S II] 6731 Å images, improvement of analysis techniques are needed
- Complete analysis of STIS ion lines
- Correlation with other datasets (e.g. volcanic activity, positions of other moons, flux tube footprint, etc.)

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